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INVESTIGATION OF THE MODIFIED LOTTMAN TEST TO PREDICT THE STRIPPING PERFORMANCE OF PAVEMENTS IN COLORADO

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The contents of this report reflect the views of authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Colorado Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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16. Abstract

Moisture damage to hot mix asphalt pavements has been a sporadic but persistent problem in Colorado even though laboratory testing is performed to identify moisture susceptible mixtures. The laboratory conditioning was often less severe than the conditioning the hot mix asphalt pavement encountered in the field.

Twenty sites of known field performance with respect to moisture susceptibility, both acceptable and unacceptable, were identified. Material from these sites were tested using seven versions of the modified Lottman test (AASHTO T 283) and the boiling water test (ASTM D 3624).

For modified Lottman testing, two levels of severity for conditioning laboratory samples were identified that correlated well with conditions in the field. For mixtures placed under high traffic, high temperatures, high moisture, and possible freeze, the severe laboratory conditioning defined in the report should be used. The milder laboratory conditioning defined in this report is appropriate for low traffic sites.

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I. INTRODUCTION

Moisture damage, otherwise known as "stripping", to hot mix asphalt (HMA) pavements has been a sporadic but persistent problem on projects in Colorado. After premature moisture damage was observed on a specific project in July of 1991, the Asphalt Institute was requested to perform a joint study with the Colorado Department of Transportation (CDOT). The results of the joint study were reported by McGennis (1) in October of 1992. Recommendations included:

- evaluating aggregates of known field performance with several versions of the moisture susceptibility test used by Colorado,
- evaluating aggregates of known field performance without lime or liquid anti-stripping additives,
- evaluating the sand equivalent test,
- implementing a better P200 management strategy during construction,
- limiting the quantity of P200 in HMA, and
- milling ruts instead of using leveling courses.

This report presents results from the first two recommendations; all of the other recommendations have been investigated and implemented. The purpose of this report is to compare HMA pavements of known field performance with results from various laboratory moisture susceptibility tests. The laboratory tests investigated were the modified Lottman (AASHTO T 283) and various versions, and the boiling water test (ASTM D 3625).

Excellent literature reviews on tests used to identify moisture susceptible mixtures and causes of moisture damage can be found in References 2 and 3.

II. SITE SELECTION

Twenty sites were selected throughout Colorado with a known history of performance with respect to moisture damage. Performance of the sites was categorized as good, high maintenance, disintegrators, or complete rehabilitation. The sites are listed in Table 1 based on their performance category and labeled by county or nearby city.

Table 1. Sites Used in This Study.

Site	Location	Category
1	Glenwood Springs	Good
2	Craig	
3	Delta	
4	Fruita	
5	Grand Junction	
6	Durango	
7	Ft. Collins	
8	Nunn	High Maintenance
9	Denver	
10	Douglas County	
11	Aurora	
12	Jefferson County	
13	Cedar Point	Complete Rehab.
14	Agate	
15	Arriba	
16	Limon	
17	Trinidad	Disintigrators
18	Walsenburg	
19	Fleming	
20	Gunnison	

Good. Some aggregate sources in Colorado have a good history of providing pavements that resist moisture damage. Seven different aggregate sources with a history of excellent performance were selected for investigation. A specific project using each aggregate source was then studied in detail for this investigation.

High Maintenance. These pavements have received an exceptionally high level of maintenance. Although pavements in this category are still in service after two to five years, their performance is considered unacceptable when compared to their design life. The maintenance required to address problems from moisture damage to the HMA pavements included overlays and significant patching of potholes. A 15-month old pavement that required an overlay on some sections is shown in Fig. 1.

Disintegrators. There are several aggregate sources used in HMA pavements that have a notorious history of severe moisture damage. A 6-month old pavement that disintegrated is shown in Fig. 2. Since contractors have not used these aggregate sources on CDOT projects for many years, specific mix designs for the "disintegrators" were difficult to obtain. The mix designs with the aggregate sources thought to be "disintegrators" were reproduced as closely as possible with the help of experienced, long-term employees of the CDOT.

Complete Rehabilitation. Several pavements in Colorado required complete rehabilitation when less than two years old, and often when less than one year old. The moisture damage was related to a unique pavement design feature, rut-resistant

Fig. 1. A "High Maintenance" Mix Experiencing Raveling After 15 Months.

Fig. 2. A "Disintegrator" After 6 Months.

composite pavement, that utilized a plant mixed seal coat (PMSC) as described and evaluated by Harmelink (4). HMA pavements directly below the PMSC exhibited severe moisture damage. The pavement surface (Fig. 3) and a core showing the moisture damage that occurred just below the surface (Fig. 4) are shown for a pavement requiring complete rehabilitation after 12 months. Even though the PMSC was a contributing factor to the distress in the underlying HMA, the HMA was still considered to be susceptible to moisture damage since it failed so quickly.

The weather conditions that contributed to the failure of the pavements requiring complete rehabilitation examined in this study are shown in Figures 5 through 8. The temperature is the monthly mean maximum temperature, i.e. the average of the daily high temperatures. The precipitation is the total accumulation for the month. The first month and year in each figure represents the end of construction, and the final month and year in each figure represents the time of failure.

Pavements requiring complete rehabilitation all failed when high levels of precipitation occurred in the hottest part of the summer. Even though all pavements in Colorado are subjected to freeze cycles, the severe moisture damage did not correspond with freezing conditions. The instantaneous failures were directly related to a simultaneous combination of high temperature, high moisture, and high traffic.

The environmental data used in this report was obtained from the weather station located closest to each project and reported by the National Oceanic and Atmospheric Administration's National Climatic Data Center.

Fig. 3. The Surface of a Pavement Requiring "Complete Rehabilitation" in 12 Months.

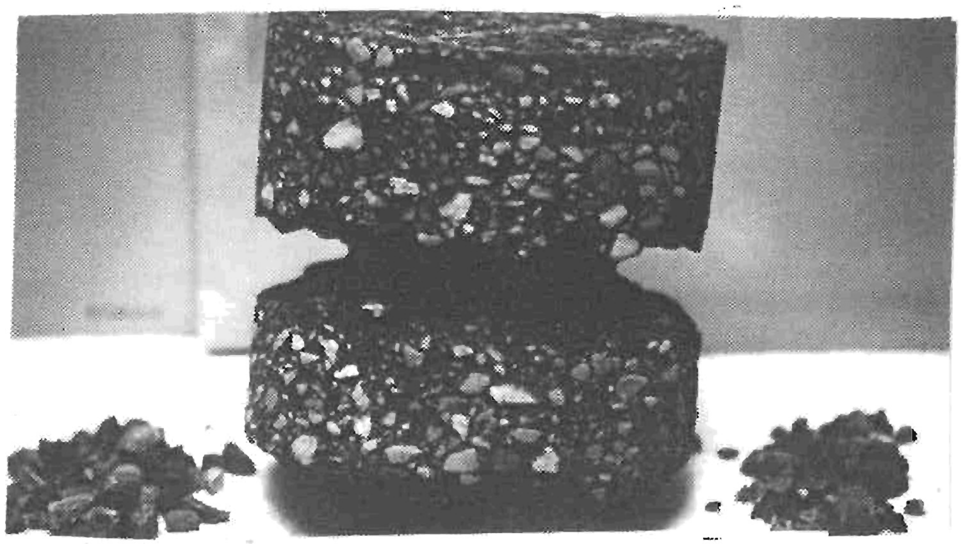

Fig. 4. A Core Showing Stripping Below the Surface from the Pavement in Figure 3.

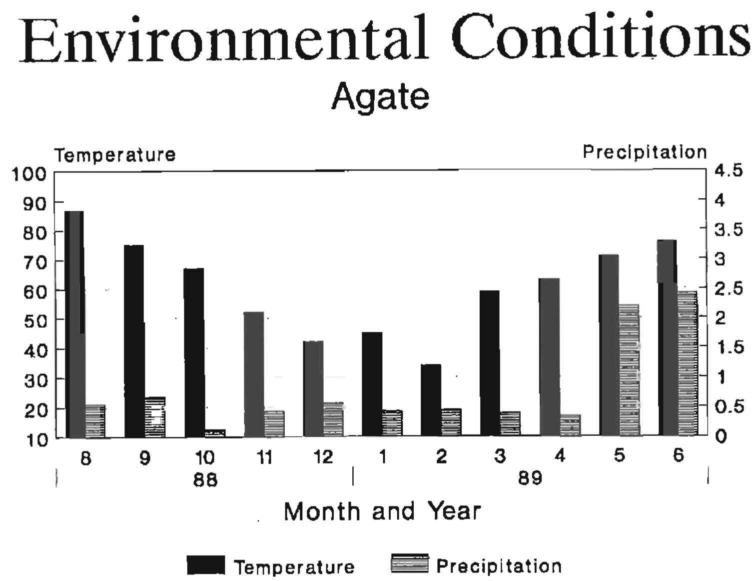

Fig. 5. Environmental Conditions for the Pavement at Agate Requiring "Complete Rehabilitation" After 12 Months.

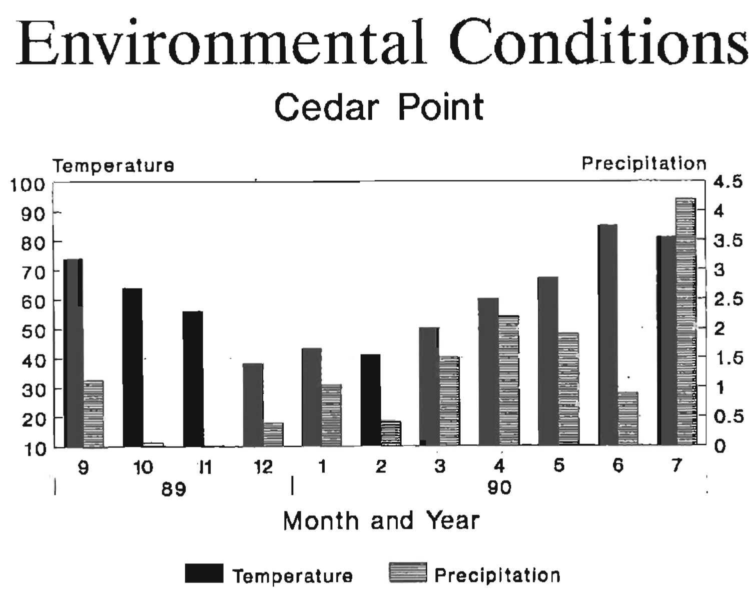

Fig. 6. Environmental Conditions for the Pavement at Cedar Point Requiring "Complete Rehabilitation" After 11 Months.

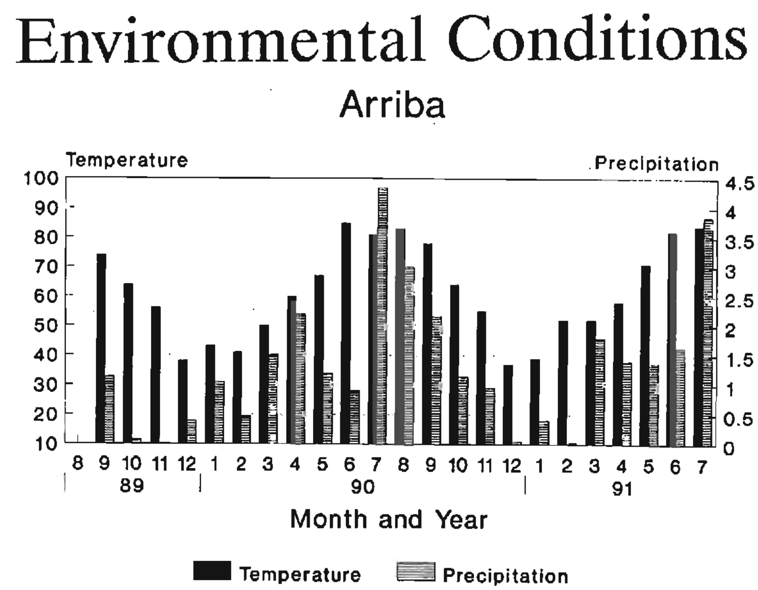

Fig. 7. Environmental Conditions for the Pavement at Arriba Requiring "Complete Rehabilitation" After 24 Months.

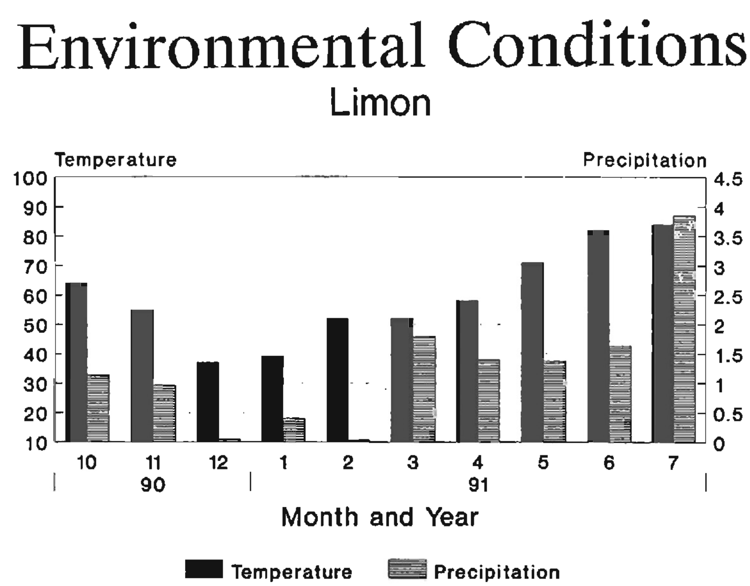

Fig. 8. Environmental Conditions for the Pavement at Limon Requiring "Complete Rehabilitation" After 10 Months.

III. TEST METHODOLOGY

The original mix design used at each site was identified. Information retrieved included the aggregate sources, percentage of each component aggregate stockpile, component and combined aggregate gradations, optimum asphalt content, asphalt cement source and grade, and anti-stripping treatment.

It was not possible to use the exact aggregates and asphalt cements from the original projects placed two to ten years ago. So, virgin aggregates from the original sources used at each site were sampled. Additionally, recently produced asphalt cements and anti-stripping treatments were obtained from the original suppliers of materials to the sites.

The aggregates from each site were then blended to match the gradation used on the project as closely as possible. A mix design was then performed to validate the optimum asphalt content from each site. When the optimum asphalt content of the new mix design matched the optimum asphalt content of the original mix design, the moisture susceptibility testing proceeded. When the optimum asphalt content of the new mix design did not match the optimum asphalt content of the original mix design, it was assumed the aggregates had changed and the new optimum asphalt content was used. No optimum asphalt contents used in this study varied by more than 0.2% from the original designs.

The aggregate gradations and optimum asphalt contents of the HMA mixtures used for this study are shown in Table 2.

Table 2. Aggregate Gradations and Optimum Asphalt Contents for HMA Mixtures Used in This Study.

Site	AC %	Gradation (mm and inches) 19.0 3/4"	12.5 1/2"	9.50 3/8"	4.75 #4	2.36 #8	0.60 #30	0.30 #50	0.15 #100	0.08 #200
1	5.5	100	87	72	51	45	26	18	10	7.0
2	4.5	100	87	74	53	42	24	15	10	6.6
3	5.3	100	93	77	53	37	21	14	9	5.9
4	4.9	100	88	66	50	40	21	14	8	5.1
5	5.0	100	94	80	52	41	31	18	10	7.1
6	6.0		100	88	51	37	22	14	10	5.9
7	5.7	100	91	74	49	37	18	12	8	4.7
8	4.8	100	94	77	49	38	24	18	12	8.1
9	5.9		100	96	62	41	25	13	10	6.1
10	5.0	100	86	77	55	43	26	18	13	8.6
11	4.9		100	97	57	40	21	15	11	7.8
12	5.0	100	86	76	54	42	25	18	13	8.4
13	5.7	100	86	78	60	45	22	15	9	5.7
14	5.3	100	86	78	63	47	25	16	10	7.7
15	5.6	100	85	76	62	49	27	18	13	8.3
16	5.4	100	88	79	61	50	30	20	13	8.3
17	5.6		100	95	72	44	24	17	12	7.3
18	5.6		100	95	70	39	21	15	11	7.2
19	5.5	100	96	93	83	69	32	20	14	11.7
20	6.5	100	96	80	50	42	26	18	12	8.3

IV. DEVELOPMENT OF THE MODIFIED LOTTMAN PROCEDURE

A modified Lottman procedure is most commonly used by the CDOT for moisture susceptibility testing of HMA. Since nation-wide experts have made numerous modifications to the procedure, understanding its historical development is critical. In Table 3, the original procedure developed by Lottman (5,6,7) is compared to the two most commonly used versions today (AASHTO T 283 and ASTM D 4867).

TABLE 3. COMPARISON OF THE ORIGINAL LOTTMAN (5) TO CURRENTLY RECOMMENDED PROCEDURES

	"Original" Lottman (Ref. 5)	Modified Lottman	
		AASHTO T 283	ASTM D 4867
Short-Term Aging	None	Loose mix: 16 hrs @ 60°C Compacted mix: 72-96 hrs @ 25°C	None
Air Voids	3% to 5% *	6% to 8%	6% to 8%
Sample Grouping	Random	Average air voids of two subsets should be equal	Average air voids of two subsets should be equal
Saturation	100% *	55% to 80%	55% to 80%
Freeze	15 hrs @ -18°C	Min. 16 hrs @ -18°C	Optional: 15 hrs @ -18°C
Hot Water Soak	24 hrs @ 60°C	24 hrs @ 60°C	24 hrs @ 60°C
Strength Property	Indirect tension or diamentral modulus	Indirect tension	Indirect tension
Loading Rate	1.6 mm/min. @ 13°C	51 mm/min. @ 25°C	51 mm/min. @ 25°C
Precision Statement for a Single Operator	10% for TSR	None	8 psi for indirect tensile strength (wet or dry)

* Not specified, but representative of a typical value encountered.

Initial Study. From 1968 through 1982, Lottman (5,6,7,8,9,10,11) developed a new test procedure to identify the moisture susceptibility of an HMA. The procedure was verified with aggregates of known field performance and through the construction of test sections.

In 1970, Lottman (10) reported that moisture damage could result from excess pore pressures that developed in the HMA pavement from traffic and thermal expansion. Therefore, the moisture susceptibility test procedure included conditioning phases that created pressure within the air voids of the HMA sample. The conditioning included high levels of saturation and a freeze cycle to create pore pressure.

In 1974, Lottman (5) calculated indirect tensile strength and modulus ratios as the value from the conditioned sample divided by the value from the unconditioned sample. Conditioning included vacuum saturation followed by either single or multiple cycles of freezing and hot-water soaking. Loading rates for the indirect tensile strengths were examined at 1.6 mm/min. (0.065 in./min.) at 13°C (55°F) and 3.8 mm/min. (0.15 in./min.) at 23°C (73°F).

Lottman (6) reported the procedure in 1978, and Lottman (7) "finalized" the procedure in 1982. Testing parameters for the "original" Lottman procedure are shown in Table 3. In 1982, field evaluations on eight test sections in seven states, including one in Colorado, provided validation of the Lottman moisture susceptibility test (7).

Loading Rate. In 1979, Maupin (12) performed a study to implement the 1978 Lottman test procedure for Virginia. For convenience of using existing equipment, he recommended a loading rate of 51 mm/min. (2 in./min.) at 25°C (77°F) instead of Lottman's recommendation of 1.6 mm/min. (0.065 in./min) at 13°C (55°F). No statistically significant difference was measured in the tensile strength ratios between the two loading rates at the corresponding temperatures.

Testing in Colorado was performed to determine the difference in the 51 mm/min. and 5.1 mm/min. loading rates. Tensile strength ratios prduced from the two different rates were identical. Dry strengths using the faster rate were 2.5 to 3 times higher than those produced from the slow loading rates.

The two modified Lottman procedures most commonly used today recommend a loading rate of 51 mm/min. (2 in./min.) at 25°C (77°F), as shown in Table 3.

Air Voids. Lottman (6) recommended compacting the laboratory sample to match the projected air voids that would be in the HMA pavement after approximately 6 years (3% to 5% air voids). In order to improve the Lottman procedure, Tunnicliff (13,14,15) recommended modification of the target air voids. The sample should be compacted between 6% and 8% air voids to simulate the in-place voids of the HMA pavement soon.

The two modified Lottman procedures most commonly used today recommend limiting air voids between 6% and 8%, as shown in Table 3.

Saturation. A sample can be damaged if it swells during the vacuum saturation process. Based on testing of aggregates of known field performance, Jimenez (16) indicated that swelling during vacuum saturation was related to stripping susceptibility. Coplantz (17) vacuum saturated samples for 30 minutes at a pressure of 610 mm of mercury to provide 100% saturation. Vacuum saturation alone did not appear to initiate a stripping mechanism. Kennedy (18) found excessive vacuum saturation alone did not create stripping unless the aggregate had shown poor stripping performance.

Stuart (19) performed testing on mixtures of known stripping performance, both acceptable and unacceptable. Based on test results from the study, there was no conclusive evidence that high saturation or over-saturation adversely effected the test results. The Lottman procedure (7) with high saturation and the modified Lottman procedure developed by Tunnicliff (15) with partial saturation were comparable.

Dukatz (20) performed testing that indicated no conclusions could be made on the effect of saturation and swell on the tensile strength of the conditioned sample. Various samples saturated to high and low levels had high and low tensile strengths.

In order to determine if partial saturation could predict pavement performance, Tunnicliff (15) tested the eight samples Lottman (7) used for field verification (6 years after Lottman). He concluded that limiting saturation levels correlated well with the Lottman procedure (7) that allows over-saturation and swell.

Tunnicliff (13) contended that damage from excessive saturation could result in low tensile strength ratios even if the HMA was not moisture susceptible. Although no test results were presented, past published (unreferenced) and unpublished literature allegedly supported his claim. Over-saturation of one sample by Tunnicliff (14) indicated that over-saturation may be too severe.

The swell of the HMA should be measured. The two modified Lottman procedures most commonly used today recommend limiting the level of saturation between 55% and 80%, as shown in Table 3.

Freeze Cycle. Tunnicliff (14,15) also recommended eliminating the freeze cycle so the test would be quicker and easier to perform for field verification.

Lottman (5) indicated that the freeze cycle with high saturation predicted the stripping susceptibility of HMA pavements, even when the HMA pavements in the field were not exposed to freezing conditions. Stuart (19) indicated that either the high saturation of low air voids with a freeze cycle recommended by Lottman (7) or the partial saturation of high air voids with no freeze cycle in the modified Lottman procedure (15) would be comparable. It was likely that the freeze was required to apply a stress in the sample as discussed by Professor B.M. Gallaway with Graf (21).

The modified Lottman procedure recommended by AASHTO and ASTM allows the freeze cycle to be optional, as shown in Table 3.

Short-Term Aging. The time of exposure of the HMA sample to a high temperature had a significant effect on the freeze-thaw pedestal moisture susceptibility test results. The longer the HMA sample had exposure to a high temperature, the more resistant it was to moisture damage (Graf, 21). The high temperature exposure increased the aging of the asphalt cement and provided better coating, or "wetting". Testing to isolate the two variables indicated the increased resistance to moisture damage was primarily related to the better coating of the aggregate.

The modified Lottman procedure recommended by AASHTO requires short-term aging whereas the ASTM version has no short-term aging, as shown in Table 3. Although Lottman (6) originally recommended the short-term aging specified in AASHTO, Lottman's (7) "finalized" procedure did not mention short-term aging.

Sample Grouping. In 1987, Dukatz (20) reported the potential for tremendous variability in tensile strength ratios if the average air voids in the conditioned and unconditioned samples were not equal. Ranges in the tensile strength ratios were as high as 0.40. When the the average air voids of the samples in the conditioned and unconditioned groups were equal, the tensile strength ratios were within a range of 0.08.

The two modified Lottman procedures most commonly used today recommend the average air voids of the conditioned and unconditioned sample groups be equal, as shown in Table 3.

Multiple Freeze-Thaw Cycles. Several researchers have investigated the use of multiple freeze-thaw conditioning cycles and have had varied conclusions. When Lottman (5) originally investigated the procedure, multiple freeze-thaw cycles were examined but over-predicted damage and were considered too time consuming for practicality. Lottman concluded one freeze-thaw cycle was adequate.

Scherocman (22) reported that multiple freeze-thaw cycles would provide a greater differentiation between the tensile strength ratios for materials with various levels of moisture susceptibility. This conclusion is supported by data presented by Coplantz (17). To the contrary, Kennedy (23) reported that rates of deterioration in tensile strength ratios using multiple freeze-thaw cycles were not statistically different for various types of materials. Materials with higher tensile strength ratios after one cycle would have higher tensile strength ratios after multiple cycles. The slopes or rates of deterioration of the tensile strength ratios were constant.

There is tremendous variability in conclusions drawn from data analysis of samples tested with multiple freeze-thaw cycles. Additionally, testing samples with multiple freeze-thaw cycles requires an additional amount of laboratory testing time that may not be readily available prior to paving. Therefore, multiple freeze-thaw cycles were not examined in this study.

The Specification. The minimum specified tensile strength ratio to ensure an HMA pavement will perform acceptably with regard to moisture susceptibility has varied. Part of the reason accounting for the specification to vary has been the changes in the test procedure. Based on testing of samples of known field performance, tensile strength ratios have been recommended at 0.70 by Lottman (5) and Maupin (12), and at 0.80 by Lottman (7), O'Connor (24), and Stuart (19). A survey of state specifications by Tunnicliff and Root (13) and Hicks (4) revealed most states used 0.70 to 0.75 but specifications ranged from 0.60 to 0.80. Computer simulations have resulted in a tensile strength ratio recommendation of 0.85 by Lottman (25).

Dukatz (20) recommended a minimum tensile strength after conditioning. A very weak sample would not be accepted. This also prevented acceptance of a mixture that had a low unconditioned tensile strength, sometimes caused by the addition of liquid anti-stripping additives. Tunnicliff (15) recommended additional research be performed to identify a minimum tensile strength requirement.

V. TEST PROCEDURES

Two different test procedures were investigated for this study: the AASHTO T 283 and the boiling water tests. Five different variations of the procedure were used. Two additional tests were performed: without any treatment for moisture susceptibility and with hydrated lime. The procedures used to investigate the moisture susceptibility of the HMA pavements of known field performance are described below. The experimental grid of tests performed on samples from the various sites is shown in Table 4.

Standard AASHTO T 283. The materials from all of the sites in this study were tested with the standard procedure (AASHTO T 283). It includes short-term aging, freezing, and limits on air voids (6 to 8%) and saturation (55 to 80%).

TABLE 4. EXPERIMENTAL GRID FOR THE STRIPPING STUDY

	GOOD PERFORMERS							HIGH MAINTENANCE					COMPLETE REHABILITATION				DISINTEGRATORS			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
AASHTO T 283	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
AASHTO T 283 No freeze	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
AASHTO T 283 30 min. sat.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
AASHTO T 283 No STA	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
AASHTO T 283 Double STA	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
AASHTO T 283 No additive	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
AASHTO T 283 Lime	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
ASTM D 3625 Boiling Water	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

STA = Short-Term Aging

AASHTO T 283 (No Freeze). In order to determine if the actual pavement performance could be predicted without the freeze cycle, the materials from all of the sites in this study were tested without the freeze cycle.

AASHTO T 283 (30-Minute Vacuum Saturation). Some investigators (17,18,20,26,27) performed the modified Lottman test by vacuum saturating a sample with 7% air voids for 30 minutes. The procedure was performed with a vacuum saturation of 30 minutes under a pressure of 610 mm of mercury. Consequently, the degree of saturation was not controlled.

AASHTO T 283 (No Short-Term Aging). The materials from all of the sites in this study were tested without short-term aging.

AASHTO T 283 (Extra Short-Term Aging). When HMA is produced for a project in Colorado, a sample is obtained and delivered to the Central Materials Laboratory for testing. After delivery, the sample is reheated for splitting into the correct sample size and reheated a second time for compaction. In total the sample is reheated approximately 4 to 8 additional hours. The effect of the additional short-term aging was investigated. The materials from all of the sites in this study were tested with an additional short-term aging of 5 hours at 121^{o}C (250^{o}F) on the loose mix.

AASHTO T 283 (No Anti-Stripping Treatment). Numerous aggregates in Colorado have moisture susceptibility problems. Anti-stripping treatments in the form of lime and liquid anti-stripping additives have commonly been used in Colorado. The use of lime began on a regional basis in the early 1960's (28). The CDOT specified the use of liquid anti-stripping additives in all mixtures in approximately 1983. Even HMA with liquid anti-stripping additives had continued problems with moisture susceptibility. The CDOT then began requiring hydrated lime in all mixtures by 1% of the weight of the aggregate in 1990.

Some aggregate sources have modified Lottman test results that are very low when no anti-stripping treatment is provided. McGennis (1) has indicated that anti-stripping treatments should be able to improve a marginal HMA mixture, but should not be expected to overcome severe deficiencies. The materials from all of the sites in this study were tested with no anti-stripping treatment to determine the "baseline" moisture susceptibility potential of the untreated HMA.

AASHTO T 283 (With Lime). Some of the HMA pavements that exhibited moisture distress were not treated with hydrated lime. The potential moisture susceptibility of these materials with 1% hydrated lime by weight of the aggregate was investigated. If an HMA of known field performance did not contain hydrated lime. When constructed, the procedure was performed on material from the site with hydrated lime.

Boiling Water Test. Several studies have indicated the boiling water test (ASTM D 3625) has accurately indicated the moisture susceptibility performance of HMA pavements. The test used for this study involved immersion of the sample in boiling water for 10 minutes. A retained coated area over 95% is usually required.

VI. TEST RESULTS AND DISCUSSION

Results from each variation in the AASHTO T 283 test are tabulated in Appendix A. The data includes air voids, saturation, swell after saturation and conditioning, conditioned and unconditioned tensile strengths, and tensile strength ratios.

Analysis of Untreated Aggregate Quality. Many of the aggregates tested in this study are moisture susceptible based on known field performance. Modified Lottman test (AASHTO T 283) results were very poor when no liquid anti-stripping additives or lime were used. The tensile strength ratios of samples tested without treatment are shown in Table 5. Just enough treatment with liquid anti-stripping additives or hydrated lime was used on each project so the HMA samples would pass the test; unfortunately conditioning in the field was more severe than conditioning in the laboratory, and the pavements failed.

It is critical that the conditioning in the laboratory (vacuum saturation, freeze, hot-water soak) be equal to or greater than the severity of conditioning expected in the field. This is especially important when marginal aggregates are used which require treatment with liquid anti-stripping additives or hydrated lime. If conditioning in the laboratory is less severe than conditioning in the field, an engineer could erroneously assume an HMA mixture would have good field performance for 10 or 20 years. Field conditions relating to moisture damage are high traffic, high temperature, high moisture, and possibly freeze.

Influence of Freeze/No Freeze/30-Minute Saturation. Tensile strength ratios for samples tested according to AASHTO T 283 (freeze), AASHTO T 283 (no freeze), and AASHTO T 283 (30-minute saturation and freeze) are shown in Table 5. No statistically significant difference was found between AASHTO T 283 performed with and without the freeze cycle.

By using the 30-minute saturation and freeze, the tensile strength ratios were significantly lower than the samples tested with partial saturation (AASHTO T 283 freeze and no freeze).

Table 5. Comparison of Tensile Strength Ratios.

Site	Tensile Strength Ratios (AASHTO T 283)			
	Freeze	No Freeze	30-Minute Saturation and Freeze	Freeze (Note 1)
1	1.02	0.85	0.98	0.37
2	1.20	1.25	1.05	0.70
3	1.11	1.22	1.20	0.37
4	1.06	0.97	1.05	0.49
5	1.10	1.07	0.97	0.92
6	0.83	0.91	0.74	0.40
7	0.97	0.89	0.86	0.90
8	0.94	0.91	0.69	0.21
9	0.95	0.90	0.72	0.40
10	0.84	0.93	0.68	0.70
11	1.11	0.96	1.09	0.38
12	1.01	1.07	0.81	0.60
13	0.69	0.64	0.56	0.45
14	0.32	0.34	0.21	0.30
15	0.53	0.46	0.32	0.35
16	0.82	0.70	0.76	0.44
17	0.65	0.51	0.30	0.55
18	0.89	0.92	0.86	0.49
19	0.22	0.20	0.28	0.24
20	0.59	0.49	0.26	0.37
Avg.	0.84	0.81	0.72	0.48
S.D.	0.27	0.29	0.31	0.20

Note 1: The HMA sample was tested without the use of liquid anti-stripping additives or hydrated lime.

In separate studies, Coplantz (17) and Dukatz (20) investigated samples compacted to approximately 7% air voids, Appendix B. They compared results from samples that were vacuum saturated for 30 minutes with a freeze and partially saturated with no freeze. They found that samples partially saturated and not subjected to a freeze cycle had tensile strength ratios that were two to three times higher than samples fully saturated and subjected to a freeze cycle.

A modified Lottman test can be performed in several different manners. Based on results from this study and others (15,17,19,20,27) shown in Appendix B, a ranking of tests in decreasing order of severity is listed as follows:

1) 30-minute saturation, 7% air voids, freeze,
2A) 30-minute saturation, 4% air voids, freeze,
2B) 55-80% saturation, 7% air voids, freeze,
2C) 55-80% saturation, 7% air voids, no freeze.

All levels of severity include hot-water soaking. Severity Levels 2A, 2B, and 2C all appear to provide approximately equal results. Severity Level 1 produces significantly lower tensile strength ratios.

The conditioning in the laboratory should be equal to or greater than the conditioning in the field. It is likely that different levels of field conditioning exist throughout Colorado. The most severe field conditions are hypothesized to be a function of:

1) high traffic,
2) high temperature,
3) high levels of moisture, and
4) possibly very low temperatures.

High levels of moisture should not be determined on an annual basis. Based upon the performance of pavements requiring complete rehabilitation, the amount of precipitation received in a high temperature period is more relevant.

The severity level of the modified Lottman test performed in the laboratory should correlate with the severity of the field conditions. If different levels of field conditioning exist throughout Colorado, then different levels of laboratory conditioning should be used.

Comparison of Tensile Strength Ratios with Actual Performance. A comparison of the various severity levels of the modified Lottman test with pavements of known field performance is shown in Tables 6, 7, and 8. A minimum tensile strength ratio of 0.80 was used.

Table 6. Comparison of Pavements of Known Field Performance with AASHTO T 283 (Severity Level 2B).

	Good	High Maint.	Complete Rehab.	Disint.
Pass	7	5	1	1
Fail	0	0	3	3

Table 7. Comparison of Pavements of Known Field Performance with AASHTO T 283 with No Freeze (Severity Level 2C).

	Good	High Maint.	Complete Rehab.	Disint.
Pass	7	5	0	1
Fail	0	0	4	3

Table 8. Comparison of Pavements of Known Field Performance with AASHTO T 283 with a 30-Minute Vacuum Saturation (Severity Level 1).

	Good	High Maint.	Complete Rehab.	Disint.
Pass	6	2	0	1
Fail	1	3	4	3

Based on these results, the best predictor of the pavements studied in this investigation is the modified Lottman test (AASHTO T 283) with a 30-minute vacuum saturation. A plot of the tensile strength ratios in ranked order is shown in Fig. 9. Although a minimum tensile strength ratio of 0.80 was used to develop Tables 6-8 and Figure 9, consideration should be given to using a minimum tensile strength ratio of 0.85, as recommended by Lottman (25).

It is known that many HMA mixtures in Colorado with good performance would fail the severity Level 1 test. The laboratory conditioning specified for a particular project should relate to the anticipated field conditions. Two levels of laboratory conditioning should exist. Severity Level 1 should be used for high traffic sites with severe environmental conditions. Severity Level 2C should be used for low traffic sites without extreme environmental conditions.

Some outliers exist and are worth noting. Site 11 is a quarried source and very fine particles conglomerated onto the large particles during processing of the aggregate. In order to minimize the generation of dust, a large quantity of water is sprayed on the aggregates. The dust stays out of the air but remains on the aggregate. After the water dries, the fine particles can be removed by scraping an aggregate with your finger nail. It is likely that the one cycle of loading applied by the modified Lottman is not severe enough to penetrate the conglomeration. A test with multiple cycles would better identify this problem.

Site 16 has been previously studied and reported by McGennis (1). Identical tests performed by the CDOT using materials sampled one year apart were substantially different.

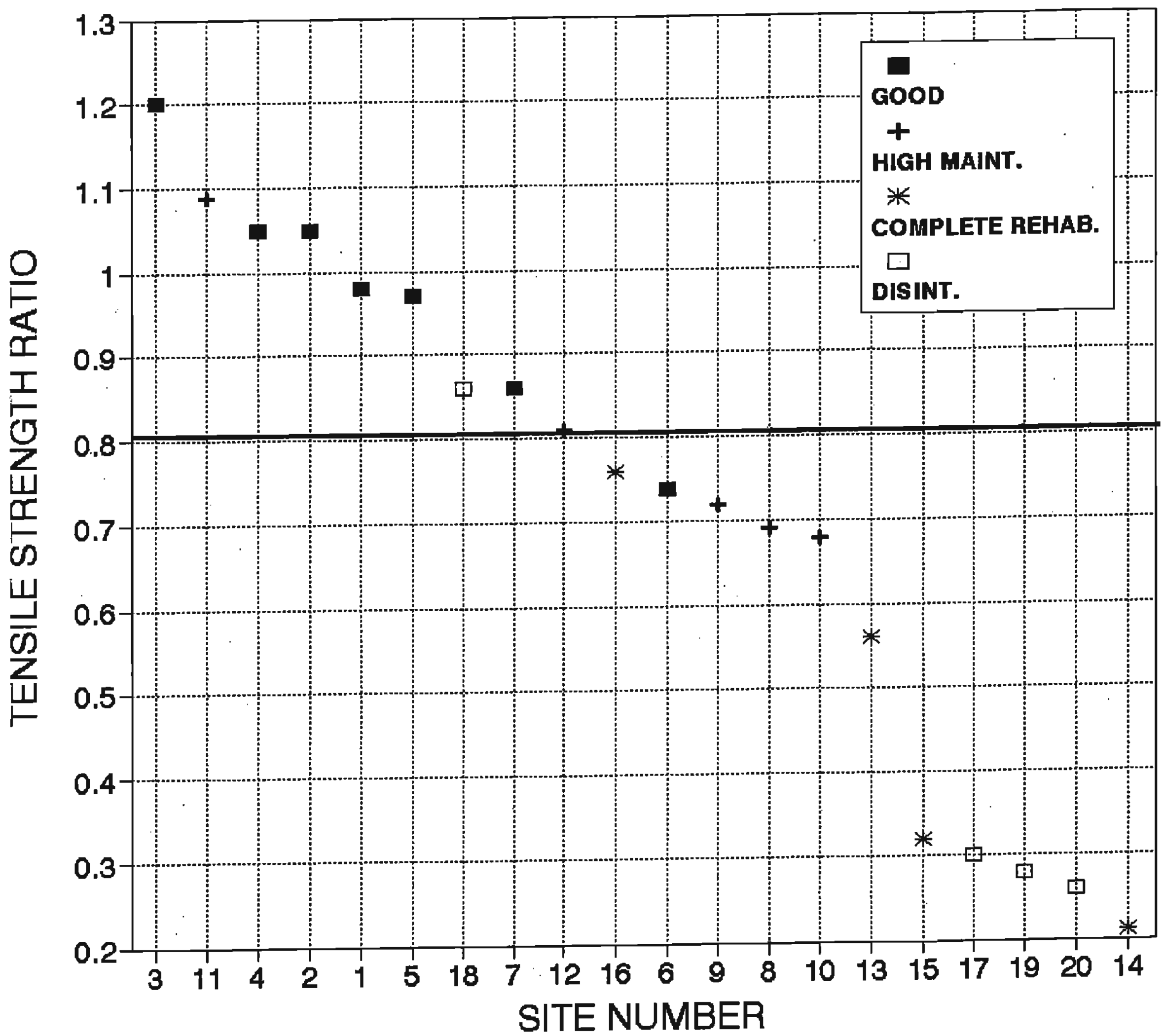

FIG.9 Ranked Order of Tensile Strength Ratios from AASHTO T 283 with a 30-Minute Saturation.

The difference is not believed to be caused by repeatability. It is well known that the quarried source is highly variable and contains seams of silt and shale. When large quantities of shale are quarried, the material is likely to be highly susceptible to moisture, as indicated by CDOT testing performed in 1992 (Ref. 1). When no shale is quarried, the material is likely to be marginally acceptable as indicated by the results in this study. Sites 10 and 12 also had the same quarried material.

Table 9. Summary of Swell After Saturation.

Site	Swell (%) After Saturation, AASHTO T 283				
	Freeze	No Freeze	30-Minute Saturation	No STA	Extra STA
1	-0.2	0.0	+0.1	-0.2	0.0
2	-0.1	-0.2	0.0	-0.2	-0.1
3	-0.4	-0.2	-0.4	+0.1	-0.4
4	-0.3	-0.3	-0.1	-0.3	0.0
5	-0.2	-0.2	0.0	-0.2	-0.2
6	0.0	0.0	+0.1	-0.1	-0.2
7	-0.6	-0.3	-0.4	-0.2	-0.3
8	-0.5	-0.4	+0.3	-0.3	-0.3
9	-0.6	-0.1	0.0	-0.5	-0.5
10	+0.2	-0.6	-0.3	0.0	0.0
11	-0.7	-0.7	-0.2	-0.2	-0.7
12	-0.5	-0.3	-0.1	-0.6	-0.8
13	-0.2	-0.4	+0.4	-0.6	-0.3
14	-0.3	+0.4	+0.8	0.0	+0.3
15	-0.1	-0.3	+0.3	0.0	0.0
16	0.0	-0.1	+0.1	-0.2	-0.2
17	-0.2	-0.2	0.0	-0.2	-0.2
18	+0.1	-0.8	-0.2	-0.2	0.0
19	+0.3	-0.1	+1.0	+0.2	+0.2
20	-0.3	+0.2	-0.2	-0.1	-0.5

STA = Short-Term Aging

If a more judicious aggregate processing scheme were practiced at the quarries that provided the aggregates for sites 10, 11, 12, and 16, a higher quality HMA pavement could be produced with these aggregates.

Analysis of Swell. Swell was measured and calculated after saturation (Table 9) and after conditioning (Table 10) according to the formulas in ASTM D 4867.

For samples saturated between 55% and 80%, there was no swell more than 0.5% after saturation. For samples saturated for 30 minutes, swell more than 0.5% after saturation only occurred on two samples (Sites 14 and 19): both had very low tensile strength ratios and poor field performance.

Swell often occurred after conditioning. The amount of swell was directly related to the tensile strength ratio and known field performance. The higher the swell after conditioning; the lower the tensile strength ratio and the more moisture damage in the field. A plot of swell after conditioning and tensile strength ratio is shown in Fig. 10 for samples with 30-minute saturation.

The sample can be damaged by swell if allowed to saturate for 30 minutes, but those materials also fail in the field based on data in this study and data reported by Jimenez (16) and Kennedy (18). Data from Coplantz (17), Stuart (19) and Dukatz (20) indicated that excessive vacuum saturation alone did not appear to initiate a stripping mechanism.

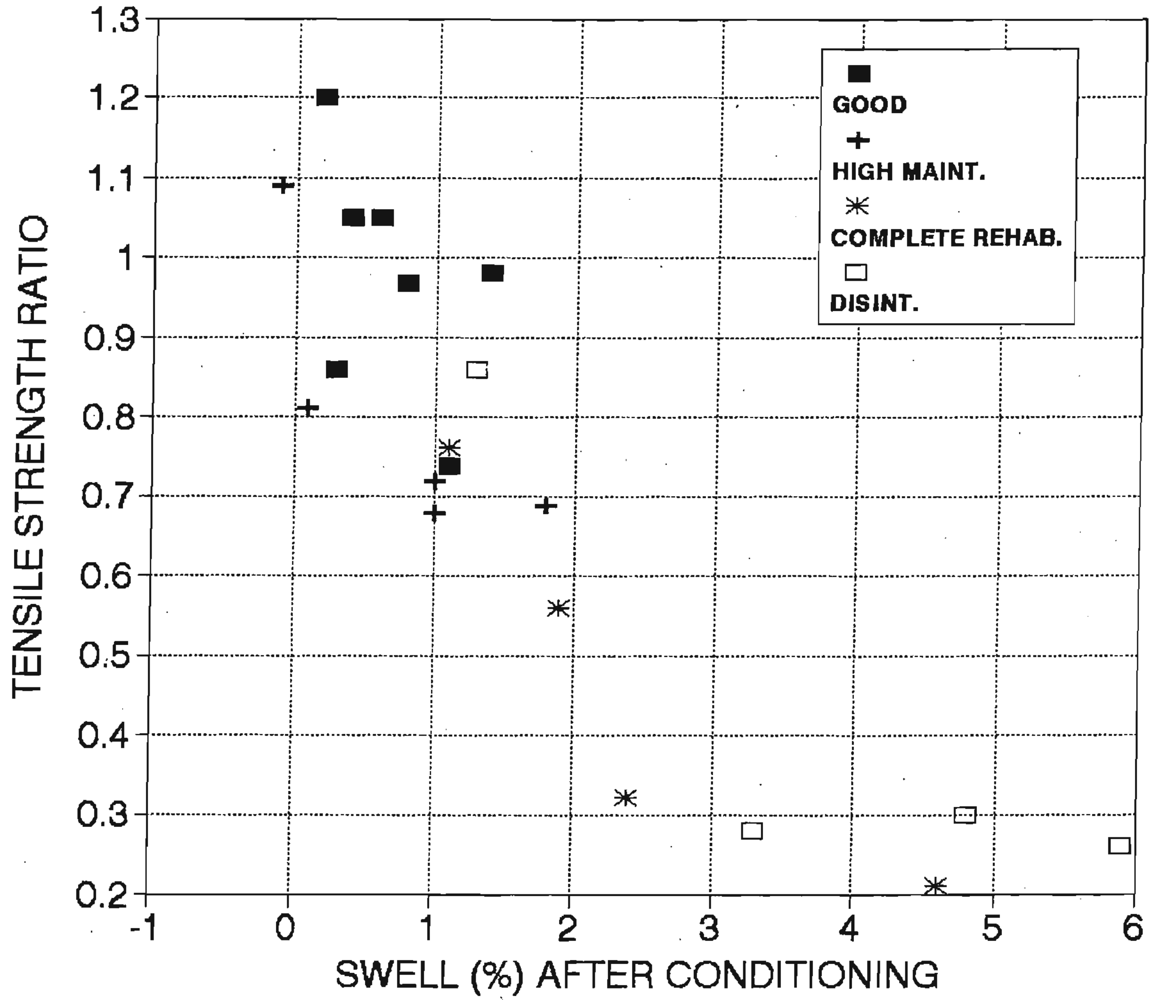

FIG. 10 Relationship of Swell After Conditioning Versus Tensile Strength Ratio from Samples Tested According to AASHTO T 283 with 30-Minutes of Saturation.

Table 10. Summary of Swell After Conditioning.

Site	Swell (%) After Conditioning, AASHTO T 283				
	Freeze	No Freeze	30-Minute Saturation	No STA	Extra STA
1	+1.1	+1.3	+1.4	+1.7	+1.3
2	+0.2	+0.2	+0.4	+0.5	+0.2
3	+0.2	+0.3	+0.2	+0.6	0.0
4	+0.6	+0.6	+0.6	+0.7	+0.7
5	+0.5	+0.6	+0.8	+0.5	+0.7
6	+0.8	+0.6	+1.1	+1.0	+0.8
7	-0.3	+0.4	+0.3	+0.4	+0.3
8	+1.3	+1.8	+1.8	+1.1	+1.2
9	+0.9	-	+1.0	-	+1.0
10	+0.3	+0.4	+1.0	+0.6	+0.2
11	0.0	+0.4	-0.1	+0.3	+0.3
12	+0.5	+0.6	+0.1	+0.6	+0.3
13	+0.9	+1.7	+1.9	+1.4	+1.4
14	+3.4	+3.9	+4.6	+4.0	+3.8
15	+1.5	+1.9	+2.4	+1.6	+2.0
16	+0.8	+0.5	+1.1	+0.5	+1.3
17	+3.3	+3.9	+4.8	+3.6	+3.4
18	+1.3	+1.0	+1.3	+1.5	+1.8
19	+8.2	+8.1	+3.3	+9.4	+10.4
20	+3.8	+4.2	+5.9	+4.3	+4.3

STA = Short-Term Aging

Analysis of Short-Term Aging. The tensile strengths of unconditioned samples (dry tensile strengths) and tensile strength ratios using three different levels of short-term aging are shown in Table 11. These values were normalized to the values obtained from the short-term aging specified in AASHTO T 283 and are plotted in Figs. 11 and 12.

Figures 11 and 12 are box plots. The line in the center of the box is the average. The box encloses plus and minus one standard deviation of data. The "whiskers" that extend out of each end of the box are the range of the data.

Table 11. Summary of Dry Tensile Strengths and Tensile Strength Ratios Using Various Lengths of Short-Term Aging (STA).

Site	Dry Strength, kPa			Tensile Strength Ratio		
	No STA	Standard STA	Extra STA	No STA	Standard STA	Extra STA
1	440	500	620	1.00	1.02	0.87
2	460	490	700	1.13	1.20	1.16
3	540	610	660	1.02	1.11	1.22
4	500	530	560	1.19	1.06	1.04
5	460	590	670	1.04	1.10	1.03
6	520	570	700	0.85	0.83	0.83
7	540	640	700	1.08	0.97	1.01
8	670	690	710	1.00	0.94	1.02
9	570	660	760	0.94	0.95	0.87
10	470	550	750	0.88	0.84	0.93
11	630	720	830	1.27	1.11	0.98
12	490	480	600	1.02	1.01	0.90
13	650	660	880	0.72	0.69	0.74
14	680	700	900	0.35	0.32	0.29
15	700	680	800	0.55	0.53	0.53
16	610	680	770	0.90	0.82	0.61
17	400	460	490	0.74	0.65	0.65
18	420	460	540	0.93	0.89	0.84
19	500	550	590	0.15	0.22	0.16
20	550	550	700	0.51	0.59	0.49
Avg.	540	589	697	0.86	0.84	0.81
S.D.	91	86	110	0.29	0.27	0.28

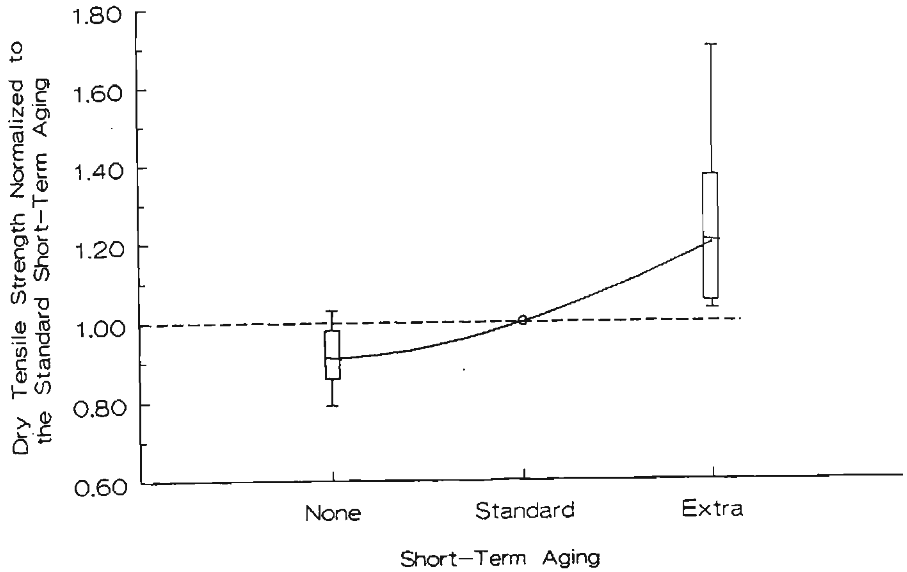

Figure 11
Influence of Short-Term Aging on Dry Tensile Strength

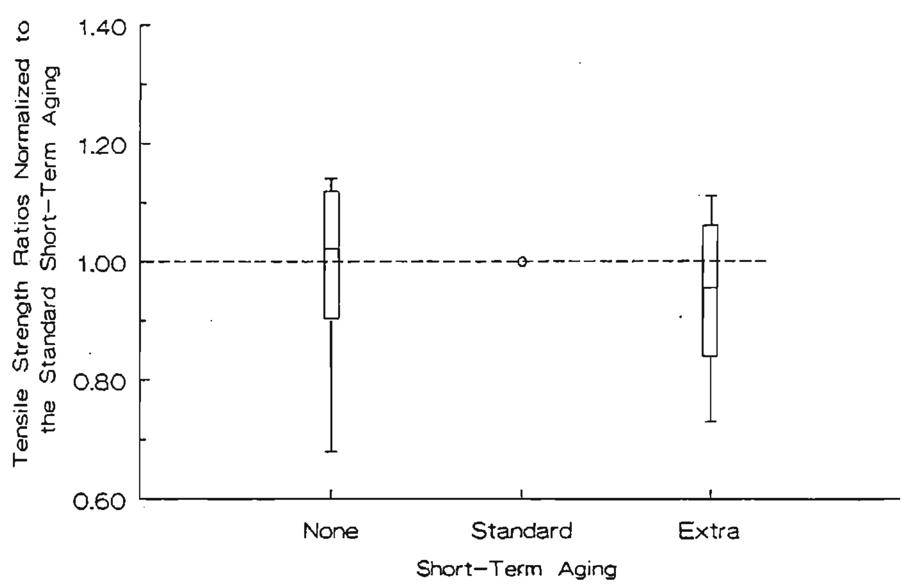

Figure 12
Influence of Short-Term Aging on Tensile Strength Ratio

The HMA samples with longer aging have higher dry tensile strengths, Fig 11. If a dry tensile strength is specified, the length of short-term aging must also be specified. The dry tensile strength did not discriminate amoung any sites. The wet tensile strength was only able to discriminate between good and disintigrator sites at about 450 kPa (65 psi).

In most cases, the tensile strength ratio remained constant with increases in aging, Fig. 12. However, in one case (Site 16), the tensile strength ratio dropped because the dry strength increased dramatically, and the wet strength did not change. The tensile strength ratio is generally insensitive to the length of aging.

Kennedy (27) also determined the effect of short-term aging on the tensile strength ratio was not significant. By eliminating short-term aging, the time required for testing could be shortened significantly.

Specifying a tensile strength ratio appears to be superior to an absolute requirement on a tensile strength of a conditioned sample. The influence of short-term aging is negated when a ratio is used. In the field, conditioning is a function of plant type, storage time in the silo, haul time, etc. With all of the field variables, it is difficult to quantify the amount of short-term aging an HMA mixture receives.

Analysis of Lime Addition. Using AASHTO T 283, all HMA samples (except one of the disintegrators, Site 19) tested in this study had acceptable tensile strength ratios when lime was used. It is not clear if the addition of lime would have provided good field performance because the severity Level 1 test was not used.

Analysis of the Boiling Water Test. The results of the boiling water test are shown in Table 12. Five people rated the samples and the test results are very subjective. A large scatter in the results was obtained between each evaluator.

The boiling water test is not an ideal test because the results are subjective. Additionally, the results do not consider the void structure, permeability, or gradation of the HMA mixture. In some mixtures the traffic loads are carried by the fine, stripping-susceptible aggregates and field performance is poor. In other mixtures with the same stripping-susceptible aggregates, performance may be good if the gradation allows the traffic loads to be carried by the coarse, nonstripping susceptible aggregates.

The permeability of the sample determined by the void structure should also be a factor in determining the susceptibility to moisture damage. The boiling water test does not consider the void structure since the test is performed on a loose mixture.

Results are summarized in Table 13 using a cutoff of 95%. The boiling test is a very severe test. Most all of the samples failed, regardless of known field performance.

Table 12. Boiling Water Test Results.

Site	Category	Coated Aggregate
1	Good	35 %
2		65
3		40
4		95
5		45
6		80
7		90
8	High Maintenance	55
9		95
10		80
11		65
12		95
13	Complete Rehab.	90
14		80
15		55
16		95
17	Disintigrators	50
18		50
19		40
20		75

Table 13. Comparison of Pavements of Known Field Performance with the Boiling Water Test (ASTM D 3625).

	Good	High Maint.	Complete Rehab.	Disint.
Pass	1	2	1	0
Fail	6	3	3	4

VII. MODIFIED LOTTMAN REPEATABILITY

The Colorado DOT performed an investigation to determine the amount of variability in the indirect tensile stripping test within the CDOT Central Materials Laboratory (29). A single operator standard deviation in the tensile strength ratio was 0.04. Maupin (30) performed a study in Virginia on the variability of the indirect tensile strength ratio. One standard deviation was 0.035. The indirect tensile strength ratio is very repeatable within one laboratory.

VIII. CASE HISTORIES OF OTHER INVESTIGATORS

The Lottman moisture susceptibility test can be performed at various levels of severity. The Colorado sites with high traffic in this study are best predicted with severity Level 1. It was of interest to determine the level of severity that predicted actual performance of other pavements reported in the literature. Four case histories in the literature were analyzed to determine the level of severity of the Lottman test that predicted actual pavement performance.

Stuart - 1986. Stuart (19) tested materials from 14 sites with good, slight and severe field performance with respect to moisture damage. The sites were from Georgia, Maryland, Mississippi and Utah and were tested with the original Lottman test (Level 2A) and the Lottman test modified by Tunnicliff (Level 2C). Both tests worked acceptably as shown in Tables 14 and 15. A minimum tensile strength ratio of 0.80 was used.

Table 14. Comparison of the Lottman Test (Level 2A) to Actual Performance.

		Actual Pavement Performance		
		Good	Slight	Severe
Lottman Test (Level 2A)	Pass	6	2	0
	Fail	0	2	4

Table 15. Comparison of the Lottman Test (Level 2C) to Actual Performance.

		Actual Pavement Performance		
		Good	Slight	Severe
Lottman Test (Level 2C)	Pass	5	1	0
	Fail	1	3	4

__**Kennedy - 1983.**__ Kennedy (18) analyzed eight sites in Texas with good and bad performance from moisture damage. Although the Lubbock site was originally classified as good, it was changed to bad when a low area revealed signs of moisture damage. The most severe version (Level 1) of the Lottman test had good correlation as shown in Table 16. A minimum tensile strength ratio of 0.80 was used.

Table 16. Comparison of the Lottman Test (Level 1) to Actual Performance.

		Actual Pavement Performance	
		Good	Bad
Lottman Test (Level 1)	Pass	2	0
	Fail	1	5

__**Kennedy - 1983.**__ One site in Texas with poor performance was analyzed by Kennedy (26). The most severe version (Level 1) of the Lottman test showed good correlation.

Parker - 1988. Parker (31) tested five aggregates from Alabama with good, moderate, and poor performance histories using the Lottman test as modified for Levels 2B and 2C. Correlation was poor as shown in Tables 17 and 18. A minimum tensile strength ratio of 0.80 was used.

Table 17. Comparison of the Lottman Test (Level 2B) to Actual Performance.

		Actual Pavement Performance		
		Good	Moderate	Poor
Lottman Test (Level 2B)	Pass	0	1	0
	Fail	2	0	2

Table 18. Comparison of the Lottman Test (Level 2C) to Actual Performance.

		Actual Pavement Performance		
		Good	Moderate	Poor
Lottman Test (Level 2C)	Pass	1	1	1
	Fail	1	0	1

Summary. The modified Lottman and numerous versions do appear to have a reasonably good correlation with mixtures of known field performance. However, the relationship is not ideal. When using a test that does not ideally relate to actual field performance, it is reasonable that a large factor of safety be applied in establishing the severity level of the test procedure and the specification value.

IX. CONCLUSIONS

The aggregates and asphalt cements used for this study were from the same sources but were not the exact material that was used on each project.

The proper performance of hot mix asphalt (HMA) pavements is not solely dependent on the material properties; improper construction or structural design could also cause problems with the HMA pavement. For the failures studied in this investigation, it is not clear how much of the failure could be attributed to materials, construction, or structural design. Material properties should have had sufficient quality to overcome minor deficiencies in construction or structural design.

1) Based on field experience, materials from 13 sites were known to be moisture susceptible. AASHTO T 283 (the modified Lottman test) results were very poor when no liquid anti-stripping additives or hydrated lime was used.

2) The conditioning performed in the laboratory (vacuum saturation, freeze, hot-water soak) should be greater than or equal to conditioning the HMA pavement will experience in the field. If conditioning in the laboratory is less severe than conditioning in the field, an engineer may erroneously assume an HMA mixture is not susceptible to moisture.

A ranking of tests in decreasing order of severity is listed as follows:

1) 30-minute saturation, 7% air voids, freeze,
2A) 30-minute saturation, 4% air voids, freeze,
2B) 55-80% saturation, 7% air voids, freeze,
2C) 55-80% saturation, 7% air voids, no freeze.

It is likely that field conditions which affect the moisture susceptibility of an HMA mixture are not the same for all areas of Colorado. The modified Lottman test should be performed at a level of severity that relates to the field conditions. Field conditions that should be considered in selecting the severity level are: traffic loadings, temperatures, moisture levels, and possibly freezing.

3) The laboratory conditioning specified in AASHTO T 283, with or without a freeze, was severe enough to accurately identify the HMA mixtures that performed well and disintegrated. The laboratory conditioning was not severe enough to identify the HMA mixtures that required high levels of maintenance.

4) The laboratory conditioning specified in AASHTO T 283 using a 30-minute saturation period was severe enough to adequately identify the HMA mixtures that required high levels of maintenance or complete rehabilitation as being susceptible to moisture. A minimum tensile strength ratio of 0.80 was used. Consideration should be given to a minimum tensile strength ratio of 0.85.

It is known that many HMA mixtures in Colorado with good performance would fail the severe test. The laboratory conditioning specified should relate to the anticipated field conditioning. Two levels of laboratory conditioning should exist. Severity Level 1 should be used for high traffic sites with extreme environmental conditions. Severity Level 2C should be used for low traffic sites without extreme environmental conditions.

5) Swell only occurred after vacuum saturation in HMA samples that were highly susceptible to moisture damage and vacuum saturated for 30 minutes. This is in agreement with others (17,18,19,20). Data was not discovered in this study to support the limits on levels of saturation to prevent swell as proposed by Tunnicliff (13,14,15).

   There was a relationship between the swell after conditioning, the tensile strength ratio, and known field performance. The more a sample swelled, the lower the tensile strength ratio, and the worse the field performance.

6) When HMA samples have longer periods of short-term aging, the dry tensile strengths increase. However, the tensile strength ratios remain constant because the wet and dry tensile strengths generally increase proportionately.

   Since the short-term aging does not significantly influence the tensile strength ratio, it could probably be skipped to shorten testing time.

7) The boiling test is a very severe test. Most all of the samples failed, regardless of known field performance. The boiling water test does not consider gradation, void structure, or permeability, all of which influence field performance related to moisture susceptibility.

X. IMPLEMENTATION

A laboratory moisture susceptibility test should condition samples to a level of severity equal to or greater than the conditioning that will be encountered in the the field. For the variety of traffic and environmental conditions in Colorado, the laboratory test should be performed at one of two levels of severity.

Severity Level 1 should be used in high traffic areas, areas experiencing high temperatures simultaneously with high moisture, and possibly wet-freeze areas. The severity Level 1 test includes:

1) no short-term aging,
2) samples compacted to 6-8% air voids,
3) saturation for 30 minutes with 610 mm of mercury,
4) a minimum 15-hour freeze, and
5) a 16-hour soak in a high-temperature water bath.

Severity Level 2C (ASTM D 4867) should be specified for low traffic highways or areas without extremely high temperature and moisture conditions. The severity level 2C test includes:

1) no short-term aging,
2) samples compacted to 6-8% air voids,
3) 55% to 80% saturation,
4) a 16-hour soak in a high temperature water bath.

A team should be assembled to decide the criteria to distinguish when each of the two levels should be specified.

XI. RECOMMENDATIONS FOR FUTURE RESEARCH

The ultimate test should relate to performance in the field. The ultimate test should include:

1) a compacted sample that is saturated,
2) testing in a high temperature environment,
3) testing with repeated loadings with high pressures,
4) and a ratio of conditioned and unconditioned results.

Both the Environmental Conditioning System developed by SHRP and the Hamburg wheel-tracking device have these potential attributes.

Additional testing with the Hamburg wheel-tracking device and the Environmental Conditioning System on samples from these sites could provide validation for tests that better relate to the actual field conditions. Testing of samples used in this study with the original Lottman procedure would also be of interest.

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APPENDIX A

Summary of Laboratory Test Data

Table A-1. Test Results from AASHTO T 283

SITE	Air Voids %	Sat. %	Swell %		Tensile Strength, psi		TSR
			Sat.	Cond.	Cond.	Uncond.	
1	7.21	61	-0.2	1.1	73	72	1.02
2	6.31	62	-0.1	0.2	85	71	1.2
3	6.16	63	-0.4	0.2	98	89	1.11
4	7.8	67	-0.3	0.6	82	77	1.06
5	7.82	65	-0.2	0.5	93	85	1.1
6	6.32	58	0	0.8	69	83	0.83
7	7.04	63	-0.6	-0.3	89	92	0.97
8	6.77	65	-0.5	1.3	95	100	0.94
9	6.49	58	-0.6	0.9	90	95	0.95
10	6.64	63	0.2	0.3	68	80	0.84
11	6.76	56	-0.7	0	116	105	1.11
12	6.75	67	-0.5	0.5	69	70	1.01
13	7.03	59	-0.2	0.9	66	96	0.69
14	7.34	64	-0.3	3.4	32	101	0.32
15	7.42	58	-0.1	1.5	53	99	0.53
16	7.09	56	0	0.8	82	99	0.82
17	7.81	68	-0.2	3.3	43	66	0.65
18	6.88	59	0.1	1.3	60	67	0.89
19	7.36	68	0.3	8.2	17	79	0.22
20	7.26	60	-0.3	3.8	47	79	0.59

Table A-2. Test Results from AASHTO T 283 (No Freeze)

SITE	Air Voids %	Sat. %	Swell %		Tensile Strength, psi		TSR
			Sat.	Cond.	Cond.	Uncond.	
1	6.89	70	0	1.3	63	73	0.85
2	7.42	65	-0.2	0.2	86	68	1.25
3	6.38	63	-0.2	0.3	104	85	1.22
4	7.67	58	-0.3	0.6	80	83	0.97
5	7.78	70	-0.2	0.6	87	81	1.07
6	6.56	59	0	0.6	71	78	0.91
7	7.45	62	-0.3	0.4	82	92	0.89
8	6.84	62	-0.4	1.8	87	96	0.91
9	6.2	61	-0.1		86	96	0.9
10	6.41	60	-0.6	0.4	78	85	0.93
11	6.64	59	-0.7	0.4	106	110	0.96
12	6.64	59	-0.3	0.6	74	69	1.07
13	7.33	70	-0.4	1.7	63	98	0.64
14	7.01	60	0.4	3.9	35	102	0.34
15	7.52	70	-0.3	1.9	41	89	0.46
16	7.16	63	-0.1	0.5	68	98	0.7
17	8.09	68	-0.2	3.9	35	69	0.51
18	6.81	57	-0.8	1	66	72	0.92
19	7.52	69	-0.1	8.1	16	78	0.2
20	7.5	50	0.2	4.2	41	83	0.49

Table A-3. Test Results from AASHTO T 283 (No Short-Term Aging)

SITE	Air Voids %	Sat. %	Swell %		Tensile Strength, psi		TSR
			Sat.	Cond.	Cond.	Uncond.	
1	7.15	72	-0.2	1.7	64	64	1
2	6.91	65	-0.2	0.5	75	66	1.13
3	6.56	63	0.1	0.6	80	78	1.02
4	7.16	60	-0.3	0.7	87	73	1.19
5	7.75	62	-0.2	0.5	70	67	1.04
6	7.02	58	-0.1	1	64	75	0.85
7	7.18	56	-0.2	0.4	84	78	1.08
8	6.58	58	-0.3	1.1	97	97	1
9	6.64	62	-0.5		77	82	0.94
10	7.17	66	0	0.6	60	68	0.88
11	6.65	59	-0.2	0.3	117	92	1.27
12	6.67	63	-0.6	0.6	68	71	1.02
13	7.47	56	-0.6	1.4	67	94	0.72
14	7.68	59	0	4	35	99	0.35
15	6.8	72	0	1.6	56	102	0.55
16	6.85	60	-0.2	0.5	80	89	0.9
17	7.96	68	-0.2	3.6	43	58	0.74
18	7.52	61	-0.2	1.5	56	61	0.93
19	8.11	74	-0.2	9.4	11	73	0.15
20	7.27	61	-0.1	4.3	41	80	0.51

Table A-4. Test Results from AASHTO T 283 (Extra Short-Term Aging)

SITE	Air Voids %	Sat. %	Swell %		Tensile Strength, psi		TSR
			Sat.	Cond.	Cond.	Uncond.	
1	7.76	85	0	1.3	78	90	0.87
2	6.95	60	-0.1	0.2	118	102	1.16
3	6.59	63	-0.4	0	117	96	1.22
4	7.62	63	0	0.7	84	81	1.04
5	7.76	63	-0.2	0.7	101	97	1.03
6	6.59	63	-0.2	0.8	85	102	0.83
7	7.27	60	-0.3	0.3	102	101	1.01
8	7.08	67	-0.3	1.2	106	103	1.02
9	6.75	56	-0.5	1	95	110	0.87
10	6.59	59	0	0.2	100	108	0.93
11	6.54	62	-0.7	0.3	119	121	0.98
12	6.39	63	-0.8	0.3	78	87	0.9
13	6.91	60	-0.3	1.4	94	127	0.74
14	7.37	62	0.3	3.8	38	131	0.29
15	7.34	63	0	2	62	116	0.53
16	7.59	65	-0.2	1.3	68	111	0.61
17	7.77	64	-0.2	3.4	46	71	0.65
18	7.02	59	0	1.8	66	78	0.84
19	7.43	73	0.2	10.4	14	85	0.16
20	7.39	63	-0.5	4.3	50	102	0.49

Table A-5. Test Results from AASHTO T 283(No Anti-Stripping Treatment)

SITE	Air Voids %	Sat. %	Swell %		Tensile Strength, psi		TSR
			Sat.	Cond.	Cond.	Uncond.	
1	6.25	54	0	5.6	26	69	0.37
2	7.48	63	-0.1	0.8	51	73	0.7
3	6.59	62	-0.4	1.4	30	82	0.37
4	7.94	67	-0.5	1.6	40	82	0.49
5	7.36	64	-0.2	0.8	76	82	0.92
6	6.27	56	0.1	1.7	33	82	0.4
7	6.49	57	-0.7	0.2	76	84	0.9
8	7.48	63	0.3	2.8	22	104	0.21
9	6.65	57	-0.3	2.7	43	106	0.4
10	6.6	61	-0.4	0.7	58	80	0.7
11	7.06	60	-0.6	2.2	41	108	0.38
12	6.26	68	-0.5	1	50	83	0.6
13	7.15	56	-0.1	1.9	42	93	0.45
14	7.24	55	0.3	3.6	32	108	0.3
15	7.49	63	0	2.1	33	96	0.35
16	7.27	59	-0.3	1.6	43	99	0.44
17	8	62	-0.2	3.4	37	67	0.55
18	7.01	63	-0.2	3.5	34	70	0.49
19	6.85	70	0.2	7.6	18	77	0.24
20	7.56	60	0.1	4.5	35	94	0.37

Table A-6. Test Results from AASHTO T 283 (Lime)

SITE	Air Voids %	Sat. %	Swell %		Tensile Strength, psi		TSR
			Sat.	Cond.	Cond.	Uncond.	
1	7.21	61	-0.2	1.1	73	72	1.02
2	6.31	62	-0.1	0.2	85	71	1.2
3	6.16	63	-0.4	0.2	98	89	1.11
4	7.16	65	-0.1	0.2	97	98	0.99
5	7.82	65	-0.2	0.5	93	85	1.1
6	5	62	0.1	0.2	62	83	0.83
7	6.44	57	-0.6	-0.1	96	88	1.1
8	6.77	65	-0.5	1.3	95	100	0.94
9	6.07	58	-0.3	0.3	112	99	1.13
10	6.26	60	-0.3	0	98	88	1.12
11	6.76	56	-0.7	0	116	102	1.13
12	6.6	59	0	0.2	78	73	1.08
13	6.67	58	-0.1	0.4	98	94	1.05
14	7.2	58	-0.3	0.8	81	92	0.88
15	7.19	74	-0.2	0.9	89	98	0.91
16	7.01	56	-0.5	0.2	97	94	1.03
17	7.73	68	-0.3	1.4	56	63	0.89
18	6.88	59	0.1	1.3	60	67	0.89
19	7.16	67	0.1	3.9	52	71	0.73
20	7.13	61	-0.2	2.5	69	79	0.87

Table A-7. Test Results from AASHTO T 283 (Total Saturation)

SITE	Air Voids %	Sat. %	Swell %		Tensile Strength, psi		TSR
			Sat.	Cond.	Cond.	Uncond.	
1	7.16	91	0.1	1.4	67	69	0.98
2	6.8	92	0	0.4	85	81	1.05
3	6.88	89	-0.4	0.2	102	85	1.2
4	7.6	93	-0.1	0.6	82	78	1.05
5	7.89	92	0	0.8	78	81	0.97
6	6.74	95	0.1	1.1	60	81	0.74
7	6.64	82	-0.4	0.3	79	92	0.86
8	7.26	98	0.3	1.8	67	97	0.69
9	6.72	91	0	1	68	94	0.72
10	6.72	87	-0.3	1	56	82	0.68
11	6.96	87	-0.2	-0.1	104	95	1.09
12	6.4	87	-0.1	0.1	65	80	0.81
13	6.98	93	0.4	1.9	49	88	0.56
14	7.49	90	0.8	4.6	20	92	0.21
15	7.29	93	0.3	2.4	27	86	0.32
16	6.83	79	0.1	1.1	75	98	0.76
17	7.8	87	0	4.8	20	65	0.3
18	6.82	61	-0.2	1.3	61	70	0.86
19	7.1	93	1	3.3	22	78	0.28
20	7.65	92	-0.2	5.9	22	85	0.26

APPENDIX B

Comparisons of Different Versions of the Modified Lottman Test from Other Investigators

TABLE B-1 **Comparison of Tensile Strength Ratios Using the Modified Lottman Test (Severity Level 2A and 2B)**

STUART (19)

Site	Severity Level 2A	Severity Level 2C
GA	0.07	0.05
GA	0.25	0.23
UT	0.77	0.55
GA	0.36	0.41
GA	0.75	0.77
MS	0.87	0.82
MS	0.85	0.76
MD	0.6	0.62
GA	0.93	0.93
GA	0.9	0.75
GA	0.87	0.89
GA	0.88	0.84
MS	0.84	0.91
MD	0.97	0.94

TUNNICLIFF (15)*

ID	0.82	0.81
FHWA	0.63	0.41
MT	0.62	0.81
VA	0.35	0.81
CO	0.22	0.64
AZ	0.21	0.45
GA	0	0.37

***The aggregates and asphalt cements used to test Severity Level 2C were sampled 6 years after the Severity Level 2A samples were tested.**

TABLE B-2 **Comparison of Tensiel Strength Ratios Using the Modified Lottman Test (Severity Level 1, 2B, and 2C)**

COPLANTZ(17)

Site	Severity Level 1	Severity Level 2B	Severity Level 2C
A	0.3	0.92	
B	0.39	0.63	
C	0.41	0.54	
E	0.61	0.89	
F	0.33	0.61	
G	0.43	0.46	
H	0	0.31	

DUKATZ(20)

L-B-L	0.34		0.72
L-F-I	0.37		0.53

TABLE B-3. Comparison of Tensile Strength Ratios Using the Modified Lottman Test (Severity Level 1, 2A, and 2C) by Kennedy

District	Severity Level 1	Severity Level 2A	Severity Level 2C
17	0.47	0.57	0.52
	1.12	1.18	1.23
	0.88	0.82	1.09
	0.91	0.82	0.97
16	0.44	0.44	0.53
	0.77	0.74	0.93
	0.6	0.56	0.7
	0.45	0.53	0.68
	0.57	0.6	0.67
13	0.53	0.43	0.7
	1.22	1.42	1.26
	0.79	0.64	0.29
	0.78	0.61	0.88
6	0.15	0.2	0.32
	0.58	0.78	0.78
	0.26	0.4	0.42
	0.3	0.49	0.42
	0.3	0.37	0.54
25	0.46	0.67	0.64
	0.93	1.3	1.07
	0.82	1.19	1.01
	0.82	0.98	1.01
	0.7	1.03	0.86
	0.72	0.92	0.87

TABLE B-3 (Continued)

District	Severity Level 1	Severity Level 2A	Severity Level 2C
1	0.8	0.74	1.01
	1.14	1.06	1.24
	1.14	1.14	1.29
	0.82	0.7	0.95
	1.1	1.1	1.2
	1.17	1.07	1.22
	1.5	1.21	1.42
	0.94	1.15	1.13
19	0.93	1.12	0.98
	1.45	1.07	1.64
	0.99	1.19	1.2
	1.11	1.25	1.36
	1.22	1.16	1.3
	1.03	0.93	1.03
21	0.22	0.24	0.77
	1.04	1.04	1.07
	0.39	0.52	0.55
	0.54	0.73	0.74
	0.3	0.35	0.37
	0.59	0.45	0.78
	0.53	0.51	0.58
	0.39	0.47	0.49